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ALGORITHMS FOR IN-LINE PRESSURE TRANSMITTERS CONDITION MONITORING

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Introduction. In the context of the transition of the world industry to new production technologies, the task of monitoring the technical condition of automatic control systems components, including pressure sensors, is urgent. Despite the existence of research and development aimed at creating systems for diagnostics and self-diagnosis of pressure sensors, the degradation mechanisms of mechanical parts of sensors and diagnostics algorithms during operation remain insufficiently studied.

Aim. Propose algorithms for condition monitoring of the mechanical and hydraulic system of in-line pressure transducers.

Materials and methods. This study is based on tests conducted on pressure modules with defects that simulate the lack of liquid in the separation cavity of the mechanical and hydraulic system of the transducer, manufactured by the industrial partner. The method of fault diagnosis is based on the analysis of statistical characteristics of the ADC signal of the pressure modules.

Results. During the tests, hypotheses were confirmed about the dependence of the standard deviation of the output signal of the pressure module on the volume of liquid-oil in the channel. Based on the obtained data, algorithms for diagnosing the technical condition of the pressure sensor were proposed, which use the values of the sensor signal STD as a diagnostic parameter. The algorithms provide verification of the applicability conditions of the considered method and use additional information about the technological process. The problems that need to be solved for the practical implementation of algorithms in real production are formulated.

Conclusion. The proposed algorithms for condition monitoring of the pressure sensor differ from the known diagnostic algorithms in that they use the results of experimental studies and are aimed at detecting a malfunction of the mechanical part of the sensors. Algorithms can be used to monitor the technical condition of in-line pressure sensors during operation under certain conditions that need to be clarified in the course of further research and field tests.

Keywords: condition monitoring, pressure transducers, fault detection, noise analysis, standard deviation.

Introduction

In the context of the transition of the global industry to new digital and intelligent production technologies, the key is to use a large amount of data that is transmitted and processed digitally. The source of the data, as a rule, are the sensors and other measuring devices. Features of Industry 4.0 include sensor revolution – a mass transition to the use of digital sensors, actuators and automatic control systems [1]. The number of sensors used in various applications of Industry 4.0 is increasing at an enormous rate.

At the same time, the problem is not only an increase in the number of sensors, but also an increase in the requirements for the measurement quality. Since it is assumed to manage all technological objects and processes based on mathematical models and digital data, the increasing challenges of digital condition monitoring of equipment and automation of production processes increase the requirements for the new measurement, control and diagnostics techniques. The development of digital, intelligent production technologies leads to an increased need for intelligent sensors of a new type. The growing number of sensors and their integration into automatic control systems requires new approaches to the methods of their metrological maintenance.

Due to the fact that the equipment is subject to break during operation, the task of monitoring its technical condition is relevant, especially at present, in the context of transition to new production technologies. Sensors are key elements of the automatic control system and the reliability of the entire system depends on the their reliability.

Many papers describe diagnostics and forecasting of various technical systems, in particular, there are works related to online monitoring of technical condition and self-diagnostics (self-check) of pressure sensors. Various solutions to the problem of increasing the reliability of sensors during operation are proposed, from redundant sensors to the development of new designs of pressure sensors with the function of self-diagnosis or metrological self-check [2–8].

Mass-produced pressure sensors have implemented algorithms for basic diagnostics of their own condition. There are also developments that allow condition monitoring of the technological process based on sensors of physical quantities [9–11]. There are works devoted to the study of possible errors of pressure sensors during operation and their signatures [12–16]. Nevertheless, the mechanisms of degradation of the mechanical parts of sensors and their manifestation in the sensor signals available for monitoring are insufficiently studied [14]. Overcoming this problem is an urgent task for the development of industry.

In this paper, we consider the problem of diagnostics of the technical condition of the mechanical and hydraulic system of an in-line pressure transmitter during operation. The paper suggests ideas for implementing diagnostic algorithms based on tests of pressure transmitters. The result of the study is that in conjunction with the pressure sensor manufacturer, an experimental study of the effect of sensor fill-oil leakage on the characteristics of sensor output signal was conducted. The results obtained will allow to refine the program of research and development work to create a full-fledged system for sensor condition monitoring.

1. A pressure transmitter fault symptoms

In this paper, we have studied in-line gauge pressure transmitters. The mechanical and hydraulic system (MGS) of a pressure transmitter is a part of the sensor that is directly affected by the working medium. The main function of the MGS is to transform the pressure of the working medium into the strain of the measuring membrane of the transmitter. Failure of the system leads to its inability to transmit the pressure of the working medium to the measuring membrane and the sensor becomes inoperable. For example, fill-oil leakage leads to a violation of the mechanical connection between the measured medium and the sensor. The failure of this system is manifested as a lack of technical ability to perform the required function.

The condition of the mechanical and hydraulic system is characterized by its physical parameters – mass, stiffness, geometry, etc. Defects in the mechanical and hydraulic system can lead to its failure, but in general it can perform its function even if minor defects occur, although the conversion function changes and the measurement error increases [12].

It was not intended to make changes to the design of sensors, so it was decided to select a method for sensor condition monitoring based on the output signal noise analysis. A review of the literature and theoretical analysis allowed us to formulate hypotheses that were tested experimentally during tests of faulty pressure modules. A total of 6 normal and 14 faulty pressure modules were tested.

The faulty modules simulating fill-oil leakage were manufactured by the industrial partner. The modules differed in the percentage of remaining liquid – from 53 % to 94 %. The percentage of remaining liquid corresponds to the stage of development of this fault, which allows us to investigate not only the presence of this fault, but also to determine at what stage it can be detected by the proposed method.

The tests were conducted using specialized test facility at SUSU, which allows you to regulate the flow rate of the working medium and its pressure up to 500 kPa. The tests were performed at room temperature. The pressure was controlled using the pressure sensor BD SENSORS DMP 331. The required pressure was set by regulating the actuators – the GRUNDFOS pump and the regulating valve.

According to the test results, all modules were divided into two groups. The first group consists of modules with fill-oil from 53 % to 87 %. The second group consists of modules with fill-oil of 89 % or more. The behavior of the first group (which can be considered faulty) is distinguished by the minimum value of the standard deviation (STD) of analogue-to-digital converter (ADC) output signal, which is constant with the input pressure, as well as the weak influence of the input pressure on the average value of the ADC codes (when the pressure increases above 100 kPa). The dependence of the average value and the output signal STD for modules with a fill-oil of 83–87 % is shown in fig. 1. For comparison, fig. 1 also shows a dependency graph for the module with a 94 % fill-oil.

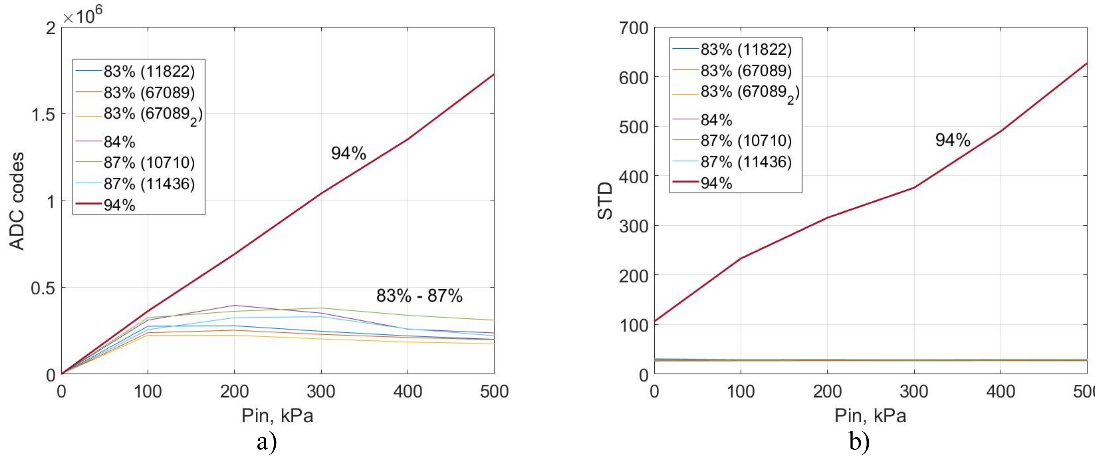

Fig. 1. The dependence of the average value (a) and STD (b) of ADC codes for the first group of faulty modules in comparison with the module with 94 % fill-oil

Fig. 1 shows that the STD of the output signal of faulty modules with fill-oil of 87 % or less does not depend on the input pressure and takes a minimum value approximately equal to the STD value at zero overpressure. For the second group of modules (with fill-oil of 89 % or more), this effect is not observed or is not always observed, and their behavior is indistinguishable from the behavior of healthy modules.

Fig. 2 shows the interval estimates of the STD of the sensor output signal for modules with different fill-oil percentages at an input pressure of 500 kPa, where the vertical value stands for the sample STD estimate with an interval of ±2σ, and the horizontal value stands for the percentage of fill-oil.

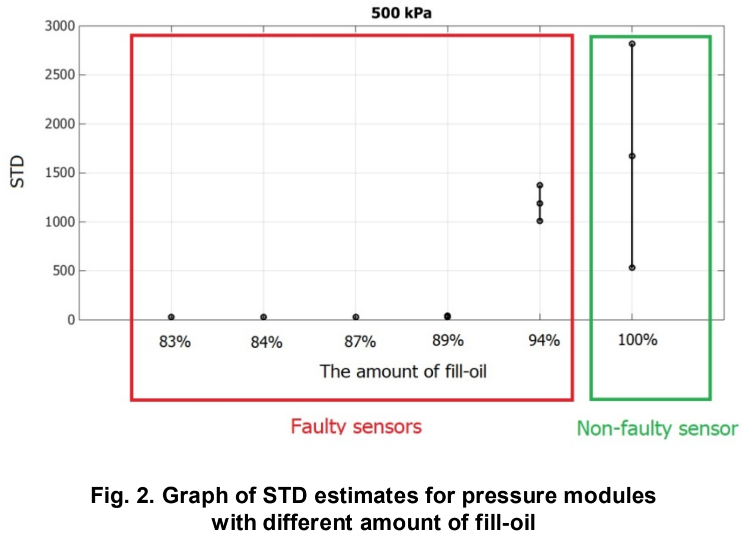

Fig. 2. Graph of STD estimates for pressure modules with different amount of fill-oil

The hypothesis of the dependence of the noise STD on the amount of fill-oil was confirmed. The value of the STD of the output signal from the pressure sensor can act as a diagnostic parameter of the pressure transmitter condition. This value can be used in pressure sensor monitoring systems. The conducted tests confirmed the possibility of using the ADC codes of the sensor as the basis of the method of diagnostics of its technical condition and allow us to offer possible diagnostic algorithms.

2. Algorithms for sensor condition monitoring during operation

Currently, the transition to new production technologies raises the question of the possibility of implementing systems for on-line condition monitoring of sensors, and increasing the calibration interval or completely abandon their scheduled metrological maintenance, as well as more economical ways to preserve or improve the reliability of automatic control systems.

The traditional way to ensure reliability is redundancy. Many important systems have triple redundancy. It is known that for condition monitoring of a pressure sensor only according to its indications, it is necessary to use at least three pressure sensors measuring the same medium under the same conditions [13]. If the readings from one of the sensors differ significantly from the readings from the other two, it can be concluded that this sensor is faulty.

In [14], such a monitoring system is used at nuclear reactors for increased monitoring of indications for an aggressive environment. This type of system uses redundant sensors, which are combined sensors that measure the same process parameter under the same environmental conditions.

Emerson Process Management offers a statistical process monitoring technology [10, 11] that can be used to detect anomalies in the impulse lines of various pressure transducers. This is achieved by using statistical methods to determine the characteristics of the signal received from the sensor and record their changes. This system uses mean and standard deviation values. For example, when impulse lines are plugged, the average value of the measured value remains constant, while the value of STD changes significantly. In this case, the monitoring system informs the operator that a fault has occurred.

The proposed algorithm for diagnosing the technical condition of a pressure transmitter is based on the calculation of the ADC codes STD during the sensor operation and comparing it with the reference value, which can either be pre-set when calibrating the sensor, or set at the beginning of using the sensor in the process. The study shows that in the presence of a sufficiently pronounced fault (the percentage of fill-oil leakage is more than 11 %), the output signal STD level remains at the minimum level and is constant with the input pressure. This suggests that the reference value of the STD can be set together with the zero-offset setting at zero overpressure.

Next, there are two possible ways to implement the algorithm. The first is a simple comparison of the calculated current STD value (for example, for 1 second on 20 conversions) with the minimum reference value. If the difference between the current value and the reference value of a pre-set threshold is exceeded, the message "Pay attention" is displayed. The second variant of the algorithm implementation is memorization of pairs of values (STD, mean) in the training mode for this technological process. In monitoring mode, every two newly calculated values (STD, mean) are compared with the database of values. If for this mean value, the current STD value is significantly less than the value from the database, an error message is returned. The specific numerical values and the details of calculating the reference values depend on the conditions in which the sensor is intended to be used, and must be established through application studies for a specific type of task.

The diagnostic algorithm based on monitoring of STD is similar to the well-known Statistical Process Monitoring (SPM) algorithm implemented in some Rosemount products [11], but it also has some differences. The Statistical Process Monitoring algorithm continuously calculates the mean value of the signal and its STD in the "Monitoring" mode. An alarm signal is triggered if the STD significantly decreases with the mean value unchanged.

If there is a malfunction of the sensor associated with its mechanical and hydraulic system, the correct display of the pressure value will fail, so the mean value will not be unchanged. Accordingly, to implement the function of diagnostics by the sensor of its own condition, it is necessary to update the SPM algorithm, taking into account the knowledge of the nature of the sensor's fault manifestation in its output signal.

In some cases, in order to detect the sensor's failure, it is enough to monitor the value of the signal's STD. But in general, even if the condition for the presence and power of noise is met, the STD may be a necessary but not sufficient indication of a fault. In order to reliably determine the condition of the sensor, additional parameters must be monitored, such as response time or parameters related to the signal spectrum. It is probably possible to take into account the dynamics of the sensor in the form of a time constant of a transient characteristic or other parameter. It is also possible to use information from multiple sensors.

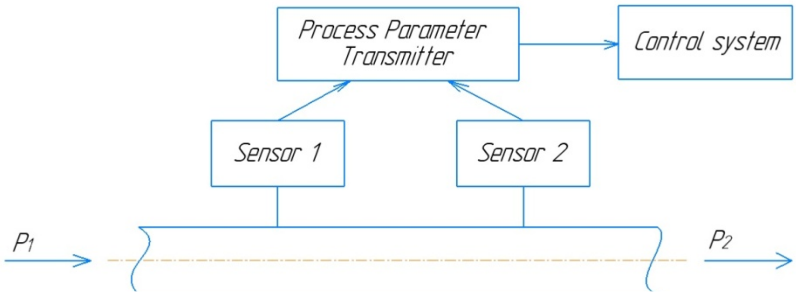

Fig. 3. Diagram of a pressure sensor monitoring system

It is possible to suggest a practical implementation of the system for condition monitoring of a pressure transmitter on the pipe section using the readings of two sensors and the values of the output signal STD. The scheme of practical implementation of this algorithm is shown in fig. 3.

The scheme consists of a pipe section with flow parameters P_1 – flow pressure at the pipe inlet, P_2 – flow pressure at the pipe outlet (subject to restrictions: P_1 is approximately equal to P_2), two pressure sensors and a transmitter of process variables that sends data to the control system. Fig. 4 shows the flowchart of the condition monitoring algorithm.

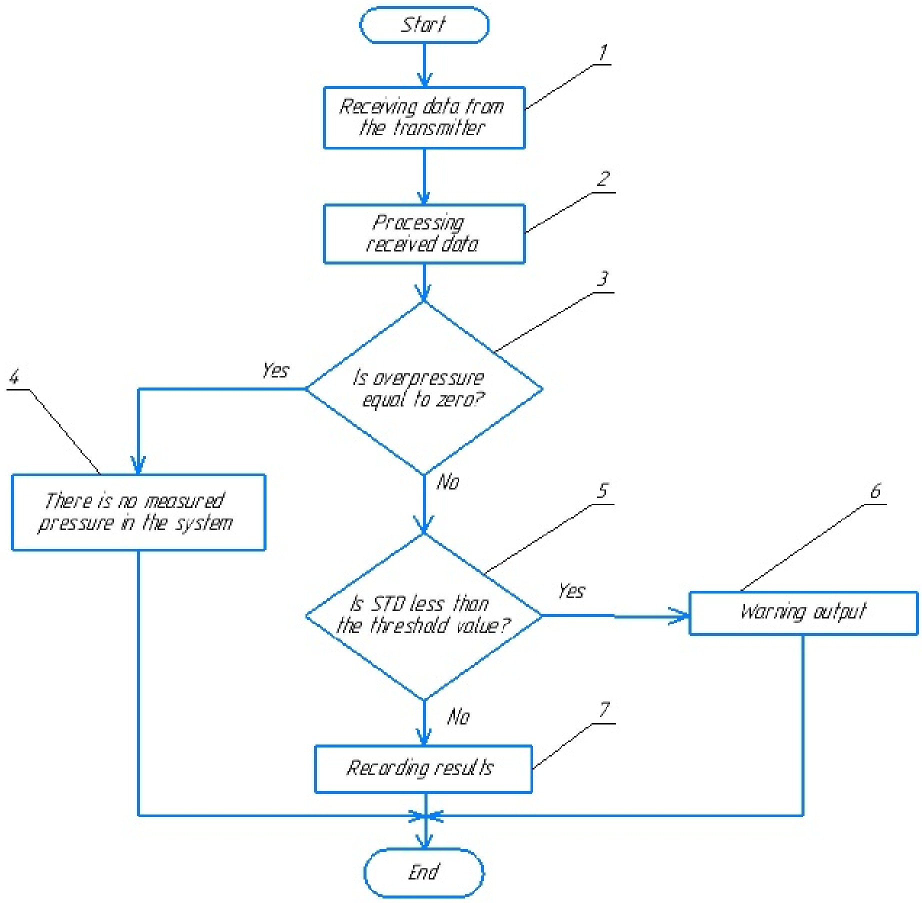

Fig. 4. Flowchart of a pressure sensor condition monitoring algorithm based on the readings of two sensors

The condition monitoring algorithm shown in fig. 4 includes a sequential set of actions. In block 1, process and variable data are obtained from pressure sensors. Further, the block 2 is the main data processing that allows you to check limitations of the method (block 3), and calculate the reference values of STD for which we can conclude about the sensor error. In block 3, data from both sensors can be taken into account. Block 5 compares the calculated values of the standard deviation with a reference value, which can either be pre-set during calibration of the sensor or calculated at the beginning of the use of sensor technology process. The final stage of the algorithm is block 7, which generates the output.

3. Applicability and limitations of diagnostic algorithms

There are limitations and conditions for the applicability of the method considered, as well as questions that have not yet been investigated or have not been finally resolved within the framework of the study. The main condition for the applicability of the method of technical diagnostics of the pressure sensor based on noise analysis is the presence of technological noise of a sufficient amplitude in the technological process, of which the pressure sensor being diagnosed is a part. Despite the fact that this condition is usually met in a real technological process, noise characteristics, which are generally unknown, can have a significant impact on the diagnostic algorithm.

The very nature of the technological process also affects the possibility of diagnostics. As a diagnostic parameter, STD is not suitable if there is zero overpressure in the process or processes that change rapidly over time. You can overcome this limitation if you use additional sources of information about the process, including data from other sensors (pressure, flow, etc.) installed to monitor the process.

The sufficient level of fault development is also a significant limitation. For failures associated with fill-oil leakage, this parameter is the percentage of liquid outflow from the separation channel. Based on the results of the study, it can be argued that the percentage of fill-oil leakage should be sufficient (more than 10 %) to change the value of the output signal STD so that it can be detected.

Conclusions

In this paper, methods for pressure transmitters condition monitoring are considered. Based on the hypothesis of the dependence of the noise amplitude on the amount of fill-oil in the pressure sensor channel, a possible scheme for condition monitoring in the pipe section is presented. The algorithm for condition monitoring is also considered in stages. This algorithm is implemented on the basis of processing the readings from two pressure sensors and analyzing the noise of the output signal. For practical implementation of algorithms, additional research is required, including the study of the influence of process noise characteristics on the possibility of detecting a fault, the search for symptoms of early development of defects and field trials.

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АЛГОРИТМЫ ДИАГНОСТИКИ ТЕХНИЧЕСКОГО СОСТОЯНИЯ ДАТЧИКОВ ДАВЛЕНИЯ ШТУЦЕРНОГО ИСПОЛНЕНИЯ

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Введение. В условиях перехода мировой промышленности к новым производственным технологиям актуальной является задача мониторинга технического состояния компонентов систем автоматического управления, которыми, в частности, являются датчики давления. Несмотря на наличие исследований и разработок, направленных на создание систем диагностики и самодиагностики датчиков давления, остаются недостаточно изученными механизмы деградации механических частей датчиков и алгоритмы диагностики их состояния в процессе эксплуатации.

Цель исследования. Предложить алгоритмы диагностики технического состояния механико-гидравлической системы преобразователя давления штуцерного исполнения.

Материалы и методы. Данное исследование основывается на проведенных испытаниях экспериментальных образцов модулей давления с дефектами, моделирующими вытекание жидкости из разделительной полости механико-гидравлической системы преобразователя, изготовленных с участием производителя датчиков давления. Метод диагностики неисправности основан на анализе статистических характеристик сигнала на выходе аналого-цифрового преобразователя (АЦП) модуля давления.

Результаты. В ходе испытаний были подтверждены гипотезы о зависимости среднеквадратического отклонения (СКО) выходного сигнала модуля давления от количества разделительной жидкости в канале. На основе полученных данных были предложены алгоритмы диагностики технического состояния датчика давления, которые в качестве диагностического параметра используют значения СКО сигнала датчиков. Алгоритмы предусматривают проверку условий применимости рассматриваемого метода и используют дополнительную информацию о технологическом процессе. Сформулированы задачи, которые необходимо решить для практической реализации алгоритмов в реальном производстве.

Заключение. Предложенные алгоритмы диагностики технического состояния датчика давления отличаются от известных алгоритмов диагностики тем, что используют результаты экспериментальных исследований и направлены на выявление неисправности механической части датчиков. Алгоритмы могут быть использованы для мониторинга технического состояния датчиков давления штуцерного исполнения в процессе эксплуатации при соблюдении определенных условий, которые необходимо уточнить в процессе дальнейших исследований и полевых испытаний.

Ключевые слова: мониторинг технического состояния, датчики давления, техническая диагностика, анализ шума, среднеквадратическое отклонение.

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